Equity-efficiency trade-offs associated with alternative approaches to deceased donor kidney allocation: a ~~cost-effectiveness~~patient-level simulation

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AUTHORSHIP

BL and JAC participated in the development of the simulation model and analyses of data inputs. RJJ facilitated acquisition and interpretation of data from the UK Transplant Registry. All authors participated in the research design, performance of the research and writing of the article.

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ABSTRACT

Background: The number of patients waiting to receive a kidney transplant outstrips the supply of donor organs. We sought to quantify trade-offs associated with different approaches to deceased donor kidney allocation in terms of quality-adjusted life years (QALYs), costs and access to transplantation.

Methods: An individual patient simulation model was developed to compare five different approaches to kidney allocation, including the 2006 UK National Kidney Allocation Scheme (NKAS) and a QALY-maximisation approach designed to maximise health gains from a limited supply of donor organs. We used various sources of patient-level data to develop multivariable regression models to predict survival, health-state utilities and costs. We simulated the allocation of kidneys from 2200 deceased donors to a waiting list of 5500 patients and produced estimates of total lifetime costs and QALYs for each allocation scheme.

Results: Among patients who received a transplant, the QALY-maximisation approach generated 48,045 QALYs and cost £681 million while the 2006 NKAS generated 44,040 QALYs and cost £625 million. When also taking into consideration outcomes for patients who were not prioritised to receive a transplant, the 2006 NKAS produced higher total QALYs and costs and an incremental cost-effectiveness ratio of £110,741/QALY compared to the QALY-maximisation approach.

Conclusions: Compared to the 2006 NKAS, a QALY-maximisation approach makes more efficient use of deceased donor ~~a limited supply of~~ kidneys but reduces access to transplantation for older patients and results in greater inequity in the distribution of health gains between patients who receive a transplant and patients who remain on the waiting list.

ABBREVIATIONS

EPTS, expected post-transplant survival

HLA, human leukocyte antigen

ICER, incremental cost-effectiveness ratio

LYFT, life years from transplant

NKAS, national kidney allocation scheme

QALY, quality-adjusted life year

UKKDRI, UK kidney donor risk index

INTRODUCTION

In 2017, there were approximately 5200 patients waiting to receive a kidney transplant in the UK.[1] Because the number of patients waiting to receive a transplant far outstrips the supply of organs from deceased donors, many countries have put in place allocation systems that make the criteria for prioritising potential recipients transparent and explicit. ~~some form of rationing is inevitable~~. ~~In many countries, the approach to rationing is made explicit through the design of a national kidney allocation scheme.~~ In the UK, a matching system between recipients and deceased donors has been in place since 1972.[2] The approach to kidney allocation in the UK is subject to continuous audit and review and over the decades, the national scheme has undergone a number of revisions to address and balance considerations of both improving transplant outcomes and promoting equity in access to transplantation.[3-4]

Simulation modelling is a practical tool that can be used to evaluate or prospectively test the impact of potential changes to kidney allocation schemes.[5-7] As part of the Access to Transplantation and Transplant Outcomes Measure (ATTOM) study, we conducted a simulation exercise to explore and compare alternative approaches to allocating kidneys from deceased donors in the UK context. We approached the development of the simulation model with three key objectives in mind:

1. To simulate different approaches to kidney allocation that reflect varying degrees of emphasis on the competing objectives of efficiency ~~(maximising health gains from scarce resources)~~ and ~~promoting~~ equity ~~in access to transplantation~~.
2. To report outcomes for each kidney allocation scheme in terms of both quality-adjusted life years (QALYs) and costs.

3. To maximise use of information on individual patient and donor characteristics to inform the allocation process and to account for between-patient variability in the estimation of outcomes.

Kidney allocation concepts of interest

The last major revision to the UK kidney allocation scheme took place in 2006.[4] In this simulation exercise, we compared the 2006 national kidney allocation scheme (NKAS) to several alternative approaches, with a particular interest in exploring the feasibility of designing an allocation scheme that maximises health gains, expressed in terms of QALYs, among transplant recipients from a fixed supply of donor kidneys. The design of a QALY-maximisation allocation scheme was predicated on the following assumptions:

1. For patients awaiting a transplant, there is a treatment alternative, namely dialysis.
2. Not all donor kidneys will result in equally good survival outcomes.
3. Not all potential recipients will derive the same survival benefit from a given donor kidney.

In the QALY-maximisation scheme, for each donor kidney that becomes available, the simulation model estimates expected QALYs following transplant for each patient on the waiting list given the characteristics of both the patient and the donor kidney to be allocated. Next, the simulation model estimates expected QALYs for each patient on the waiting list if the patient were to remain on dialysis. After calculating the difference between expected QALYs following transplant and expected QALYs on dialysis, each kidney is allocated to the patient who is expected to gain the most as a result of receiving the transplant. Over the population of transplant recipients, this approach to allocation should yield the maximum total QALY gains for a fixed number of donor kidneys. This QALY-

maximisation scheme is conceptually similar to the Life Years from Transplant (LYFT) calculation previously described by Wolfe et al., but in the current simulation exercise we used UK data sources and adopted a different method to extrapolate survival using flexible parametric survival analysis in order to calculate QALYs.[8]

A new kidney allocation scheme based on the concept of longevity matching was introduced in the US in 2014. Under this concept, donor kidneys are risk-stratified using a scoring system in order to identify which kidneys are associated with better post-transplant survival. Similarly, potential recipients on the waiting list are risk-stratified based on estimates of their expected post-transplant survival (EPTS) score. The allocation policy then prioritises candidates in the top 20th percentile of EPTS scores to receive kidneys from the top 20% of donor kidneys.[9] The cost implications of this new allocation policy in the US have been estimated.[10] To test the concept of longevity matching in the UK context, we used a UK-specific kidney donor risk index (UKKDRI)[~~10~~ 11] and developed a multivariable parametric model to estimate mean post-transplant survival for potential recipients based on an analysis of historical UK Transplant Registry data.[~~11~~ 12] A key difference between our approach to estimating recipient post-transplant survival and the EPTS score used in the US kidney allocation scheme is that our survival predictions also take into account two donor characteristics: age and history of hypertension. Thus, in our simulation exercise, recipient post-transplant survival estimates for both the QALY-maximisation and longevity matching allocation schemes are recalculated for each potential donor-recipient combination.

In addition to exploring the concepts of QALY-maximisation and longevity matching, we included two other allocation concepts in our simulation exercise that were intended to reflect greater emphasis on the principle of equity in access to transplant: random allocation

and allocation based on waiting time. Table 1 provides an overview of all five allocation concepts explored in our simulation exercise.

METHODS

Characteristics of waiting list patients and donor kidneys

To simulate the composition of the transplant waiting list, we obtained data on 1948 prevalent listed patients who were recruited into the ATTOM study between November 2011 and September 2013.[~~13~~-14] Of these patients, 513 had received a previous transplant. In the absence of predictive survival models that would allow us to account for prior transplants, we excluded these patients from the simulation exercise leaving a sample of 1435 patients, whose characteristics were replicated to make up a total waiting list of 5500 patients, which reflected the size of the waiting list at the time the simulation model was designed (Table 2). During the simulation exercise, each time a patient received a transplant, a replacement was added to the waiting list to keep it constant at 5500 patients. For the donor dataset, we obtained characteristics of 2200 donors (4400 kidneys) from NHS Blood and Transplant based on a representative historical cohort reflecting the time period between January 2010 and December 2011 ~~from NHS Blood and Transplant~~(Table 3). Characteristics of individual patients and donors were assigned at the point of entry into the model so that these characteristics could be used throughout the simulation to inform the allocation process as well as to estimate survival, costs and health-state utilities. Most patient characteristics, including comorbidities, were kept constant throughout the simulation, however three characteristics were updated as simulation time progressed;

waiting time and time on dialysis were incremented on a daily basis, while patient age was incremented annually.

Model structure and assumptions

The simulation model was constructed using the software package SIMUL8 2015 Professional version (SIMUL8 Corporation, Boston, MA, USA). At the start of the simulation, prevalent waiting list patients are loaded and held in a queue while donor kidneys are assumed to arrive at a fixed rate equivalent to 1200 deceased donors per year (Figure 1). The allocation process is triggered by the arrival of each donor kidney. Using Visual Logic, SIMUL8's internal programming language, we are able to loop through patients on the waiting list to evaluate blood group and tissue compatibility for each potential donor-recipient combination and perform the necessary calculations and scoring algorithms relevant to each allocation scheme of interest. In the model, we allowed for the possibility that no appropriate match is identified for a kidney from a donor with a rare blood or tissue type. This is unlikely to happen in practice but could occur in a small proportion of cases in our simulation because the composition of the waiting list was based on a limited sample of patients who were recruited into the ATTOM study. In the current UK allocation scheme, tissue matching between the donor and recipient is determined on the basis of human leukocyte antigens (HLA); patients are separated into one of four possible HLA mismatch levels from level 1 (000-mismatched) to level 4 (poorly matched). In current practice, patients with a level 4 HLA mismatch are not eligible to receive the donor kidney through the national allocation scheme.[12,13] In order to maintain comparability between allocation schemes, we applied the same minimum criteria for blood group and HLA matching to all allocation schemes in the simulation exercise.

Once a match has been identified, the recipient and donor kidney are assembled into a single entity to simulate the transplantation event and moved to the next step in the simulation process to determine post-transplant survival and to estimate lifetime QALYs and costs. The model assumes only two events are possible following transplantation: graft failure, in which the transplanted kidney stops working, or patient death. These events are modelled as competing risks in which we randomly sample from the survival curve for each event and move the patient to the event with the earliest sampled time.[14,15] If a patient experiences graft failure, we have assumed the patient returns to dialysis and faces the same mortality risk as a patient who has been on the waiting list and receiving dialysis for >3 years. However, if the sampled value for time to death following graft failure is longer than the time the patient would have survived based on the previously sampled value to determine initial post-transplant outcomes, we replaced it with the lower value. We did not attempt to model repeat transplants in the simulation.

The model was built by developing separate sections of Visual Logic code for each step in the allocation process so that, for example, the same procedure to evaluate blood group compatibility could be called at any point in the simulation for any of the five allocation schemes. Internal spreadsheets were used extensively to perform interim calculations at the patient level, which also facilitated model checks and step-by-step verification of the simulation process.

Estimating life years, QALYs and costs

Survival models

There are three survival models underpinning time-to-event calculations to estimate post-transplant patient survival, post-transplant graft failure and waiting list survival at various points in the simulation. Each of these models was developed based on analysis of historical UK Transplant Registry data. Data on dialysis start dates were additionally obtained through linkage to the UK Renal Registry to inform the waiting list survival model. Models were fitted using flexible parametric survival analysis in order to facilitate:[~~15~~16]

1. Extrapolation of survival curves to allow calculation of mean survival in years.
2. Inclusion of relevant patient and donor characteristics as covariates to capture variability in our predictions of survival and by extension in our estimates of costs and QALYs.

A more detailed description of the method used to fit the post-transplant patient survival model is described elsewhere.[~~11~~ 12] A summary of the patient and donor characteristics that were included as covariates in each of the final models is provided in Table S1. When the survival models were used as part of the allocation process to match recipients and donor kidneys (longevity matching and QALY-maximisation), they were applied deterministically to produce mean survival estimates. When the survival models were used to inform competing risks following transplantation in order to estimate lifetime QALYs and costs, we allowed for stochastic variation.

Health-state utility estimates

Health-state utility estimates for transplant recipient and patients on the waiting list were captured in the ATTOM study using the EQ-5D-5L questionnaire. We developed multivariable regression models to identify patient characteristics that led to variations in utility scores to inform quality-adjustment of survival estimates in the simulation model (see Table S2 for a list of characteristics included in the final models).[~~16~~ 17]

Costs

The costs of maintenance dialysis and transplant surgery were estimated in the simulation by applying fixed national tariffs.[17,18] We estimated annual hospital costs using two-part regression models that were developed by analysing patient-level data from linkage of the Hospital Episode Statistics dataset to UK Renal Registry data.[18,19] Hospital costs were captured by treatment modality (dialysis vs. transplantation) and by hospital setting (inpatient vs. outpatient) and regression models included a number of patient characteristics as covariates (Table S3a and Table S3b). For transplant recipients, the annual cost of maintenance immunosuppression assumed that patients received a combination of corticosteroids, a calcineurin inhibitor (ciclosporin or tacrolimus) and an antiproliferative agent (mycophenolate mofetil or azathioprine).[20,19]

Running the simulation

For each allocation scheme, we performed three runs using a separate random number stream for each run. A single run ends when all 4400 donor kidneys have been allocated or removed from further consideration if no match has been identified. The proportion of donor kidneys for which no match was identified was approximately 1% across all simulation runs and therefore the number of patients who received a transplant was similar across allocation schemes.

Although we are primarily interested in comparing total costs and QALYs across all transplant recipients resulting from the different allocation schemes, it is also important to consider the outcomes of those patients who did not receive a transplant within the time frame of the simulation. For these patients, we made a simplifying assumption that they

face a mortality risk equivalent to remaining on the waiting list until death and used this as the basis for projecting their lifetime costs and QALYs at the end of the simulation. QALYs and costs were both discounted at an annual rate of 3.5%.[2~~10~~]

For each allocation scheme, we report the characteristics of patients who received a transplant, the distribution of life years and QALYs for transplant recipients by age group and the total discounted costs and QALYs for patients who received a transplant, for patients who remained on the waiting list and for the overall cohort. ~~To highlight the magnitude of trade-offs between efficiency and equity in access to transplantation, we also compare several key characteristics of patients who received a transplant under each scheme.~~

RESULTS

~~**Cost-effectiveness results**~~

~~The motivation behind the QALY-maximisation approach is to allocate each donor organ in a way that maximises the potential gain in health among transplant recipients, in other words to make the most efficient use of a scarce supply of kidneys. Table 2 shows that for patients who received a transplant, this approach generated the most QALYs (48,045) and also led to the highest costs (£681 million). However, Table 2 also shows that patients who were not prioritised to receive a transplant and who remained on the waiting list had worse health outcomes and generated fewer total QALYs (20,504) compared to other allocation schemes. Taking into account total costs and QALYs for both transplant recipients and patients who remained on the waiting list, longevity matching produced the fewest QALYs (65,665) and the lowest costs (£1,473 million), while the 2006 NKAS produced the most QALYs (70,569)~~

~~and the highest costs (£1,722 million). While the longevity matching and QALY maximisation schemes both generated more QALYs for transplant recipients than the 2006 NKAS, they generated far fewer QALYs for those patients who were assumed to remain on the waiting list. In incremental cost-effectiveness analysis, random allocation and waiting time allocation were both dominated; that is to say, they were both less effective and more costly than at least one of the other allocation approaches. The comparison of the QALY maximisation approach to longevity matching generated an incremental cost-effectiveness ratio (ICER) of £8,751/QALY while the comparison of the 2006 NKAS to the QALY-maximisation approach generated an ICER of £110,741/QALY (Figure 2).~~

Access to transplantation

To understand the impact of the different allocation schemes on access to transplantation, Table ~~3~~ 4 reports the age, sex and diabetes status of patients who received a transplant. Moving along the equity-efficiency spectrum from random allocation towards allocation based on QALY-maximisation, there is a notable decrease in the average age of transplant recipients. Under random allocation, which preserves the composition of the original waiting list at the start of the simulation, 31% of transplant recipients were aged ≥60 years ~~and above~~; under the QALY-maximisation approach, this proportion fell to just 4%. Allocation schemes that emphasised greater efficiency also resulted in a higher proportion of female transplant recipients and a lower proportion of transplant recipients with diabetes.

Distribution of life years and QALYs

Table 5 shows mean survival (life years) and mean QALYs for each allocation scheme. The QALY-maximisation scheme resulted in the highest mean life years and QALYs for each transplant recipient (23.6 life years, 19.3 QALYs) but correspondingly the lowest mean life years and QALYs for patients who were not prioritised to receive a transplant (6.5 life years, 5.1 QALYs). The waiting time allocation scheme resulted in the lowest mean life years and QALYs for each transplant recipient (17.1 life years, 13.9 QALYs) and also resulted in the smallest difference in survival for those who received a transplant compared to those who did not.

Although the QALY-maximisation scheme resulted in the lowest proportion of patients aged ≥60 years receiving a transplant (4%), those who did receive a transplant survived longer on average than patients aged ≥60 years under any of the other allocation schemes. This is because the QALY-maximisation scheme is selecting patients who are expected to live long enough to derive the biggest survival benefit from each donor kidney compared to remaining on dialysis.

Cost-effectiveness results

The motivation behind the QALY-maximisation approach is to ~~allocate each donor organ in a way that maximises the potential gain in health among transplant recipients, in other words to~~ make the most efficient use of a scarce supply of kidneys. Table ~~2~~6 shows total QALYs and costs for the entire cohort of patients in the simulation. ~~that for~~ For patients who received a transplant, the QALY-maximisation ~~is~~ approach generated the ~~most~~highest total QALYs (48,045) and also led to the highest costs (£681 million). However, Table ~~2~~6 also shows that patients who were not prioritised to receive a transplant and who remained on the waiting

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DISCUSSION

The allocation of deceased donor kidneys to patients who are awaiting a transplant is constrained not only by a limited supply of kidneys but also, like all resource allocation decisions in healthcare, by a limited budget. The emphasis of the literature and the debate about kidney allocation has historically focussed on donor organs as the only constraint, and in particular on the trade-off between maximising survival and ensuring equity in access to transplantation. In this research, we have explored a wider range of potential objectives in the design of a kidney allocation scheme and used simulation modelling to quantify the magnitude of trade-offs associated with moving from one allocation approach to another. In particular, this is the first patient-level simulation exercise to consider the costs associated with different approaches to kidney allocation in the UK and to report outcomes in terms of QALYs.

The motivation for the simulation exercise described in this paper was not only to explore different allocation concepts from across the equity-efficiency spectrum, but also to improve our ability to estimate variability in outcomes resulting from different approaches to allocation using patient-level data. If alternative approaches to kidney allocation result in different patients receiving transplants, then an accurate comparison of the consequences of alternative allocation schemes depends on our ability to predict variability in outcomes dependent on individual patient characteristics. This simulation exercise relied on a number of rich sources of patient-level data including the ATTOM study, the UK Transplant Registry (held by NHS Blood and Transplant), Hospital Episode Statistics and the UK Renal Registry in order to develop predictive regression models to estimate survival, health-state utilities and costs. These predictive models were used not only to estimate QALYs and costs for

transplant recipients in all five allocation schemes but also as part of the criteria to inform the kidney allocation process for the longevity matching and QALY-maximisation schemes.

Our research demonstrates the richness of information that can be generated from a patient-level simulation but we are cognisant that there are limitations to any modelling exercise. In particular, we made a number of assumptions with respect to the model structure, such as only considering first-time transplants and excluding paediatric patients as the latter group fell outside of the scope of the ATTOM study. The characteristics of the donors were based on a contemporaneous cohort with the waiting list patients in the ATTOM study but we have not attempted to model the consequences of the different allocation schemes if the composition of either the donor pool or the waiting list were to change significantly over time. Another important simplifying assumption was that patients who were on the waiting list at the end of the simulation would not receive a transplant in the future. This assumption is unlikely to be met in practice. Survival on the waiting list is on average poorer than survival following transplant, so the likely effect of this assumption is that we have underestimated total QALYs for all allocation schemes. It is difficult to anticipate the net impact of this assumption on the cost-effectiveness results. Different allocation criteria will result in different types of patients receiving transplants and by corollary, the composition of patients who remain on the waiting list will also differ between schemes. Under the waiting-time allocation scheme, patients who remain on the waiting list at the end of the simulation would in practice still have a reasonable prospect of receiving a future transplant as their likelihood of being prioritised for transplant increases with time. In contrast, under the QALY-maximisation scheme, patients who remain on the waiting list at the end of the simulation may be less likely to receive a future transplant if their expected

QALY gains from transplant decrease over time relative to new patients joining the waiting list. Rather than attempt to apply different assumptions to each allocation scheme to project what proportion or which types of patients on the waiting list are likely to receive a future transplant at the end of the simulation, we chose to implement a standardised assumption so as not to confound our ability to observe and compare the effect of the different allocation schemes themselves. Given the importance of this assumption on estimates of QALYs and costs for the total patient population, future research should focus on testing alternative assumptions, for example by exploring if a non-terminating model could achieve a steady-state outcome that can be compared across allocation schemes over a long enough period of time. As with all simulation exercises, the need to make simplifying assumptions may limit the generalisability of the results to the real world context. With these caveats in mind, simulation modelling is still an important tool that can help increase our understanding of the potential consequences of different approaches to kidney allocation under the same set of conditions in comparison to each other.

Although we chose to report lifetime QALYs and costs as the main outcomes of interest, this simulation exercise was not specifically designed with standard methods for cost-effectiveness modelling at the forefront of our approach.[2~~1~~] There were both technical and philosophical reasons that contributed to this decision. During development of the simulation model, primary emphasis was placed on the design, feasibility and coding of the different allocation schemes. Each scheme requires the simulation model to loop through all patients on the waiting list in order to evaluate donor-recipient compatibility. In the case of the QALY-maximisation and longevity matching schemes, survival predictions take into account both recipient and donor characteristics and therefore need to be recalculated for

all 5500 patients on the waiting list each time a donor kidney enters the simulation. The computational burden of the allocation process itself led to long model running times even in the absence of introducing parameter uncertainty and therefore we were unable to perform full probabilistic sensitivity analysis. On a more philosophical note, kidney allocation represents a ~~somewhat unique~~particular resource allocation problem constrained not only by a finite healthcare budget but also by a limited supply of donor organs. Conventional cost-effectiveness methods focus on maximising health gains,[2~~3~~] but in the case of kidney allocation it is clear from current policy that maximising health gains is not the only objective. For this reason, we presented incremental cost-effectiveness results ~~of all~~for the five allocation schemes ~~and~~ but refrained from evaluating ICERs with respect to a specific threshold value. The results of this simulation exercise cannot answer the question about what the objectives of a national kidney allocation scheme *should* be, but nonetheless provide insight into the magnitude of QALY and cost differences to inform the discussion about trade-offs associated with alternative allocation concepts from across the equity-efficiency spectrum.

The QALY-maximisation approach to kidney allocation was designed to maximise health gains from a limited supply of donor kidneys. This approach yielded the most QALYs for transplant recipients but also resulted in a notable decrease in access to transplantation for older patients. Although the QALY-maximisation approach made more efficient use of a limited number of kidneys, it resulted in greater inequity in terms of both access to transplantation and the distribution of QALYs between transplant recipients and patients who remained on the waiting list.

A different kind of trade-off was evident when we considered the costs associated with each of the approaches to kidney allocation. The 2006 NKAS resulted in a modest increase in total QALYs across all patients compared to the QALY-maximisation approach but also incurred much higher total costs. If the 2006 NKAS is viewed as a compromise between equity and efficiency, then the results of this simulation provide an estimate of the additional cost to the NHS of maintaining greater equity in the allocation of deceased donor kidneys.

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Table 1. Description of the five kidney allocation schemes included in the simulation exercise

Allocation concept	Description of allocation criteria considered in each scheme
Random	• Blood group compatibility and HLA match • Priority for HLA mismatch level 1 (000) • Taking the above criteria into account, allocate the kidney randomly
Waiting time	• Blood group compatibility and HLA match • Priority for HLA mismatch level 1 (000) • Taking the above criteria into account, allocate the kidney to the patient with the longest waiting time
2006 NKAS[12]	• Priority for HLA mismatch level 1 (000), taking into account whether or not patients are highly sensitised or HLA-DR homozygous • Within tiers, prioritise patients according to a points-based system based on: – waiting time – HLA match and age combined – donor-recipient age difference – location of patient relative to donor – HLA-DR homozygosity – HLA-B homozygosity – blood group match
Longevity matching	• For each donor kidney, estimate expected post-transplant survival for each patient on the waiting list • If the donor kidney has a UKKDRI score in the top 20%, then 20% of patients with the longest expected post-transplant survival are prioritised to receive the kidney • Taking the above criteria into account, allocate the kidney according to the 2006 NKAS
QALY-maximisation	• Blood group compatibility and HLA match • Priority for HLA mismatch level 1 (000) • For each donor kidney, estimate expected post-transplant QALYs for each patient and expected QALYs if each patient were to remain on the waiting list (on dialysis) • Taking the above criteria into account, allocate the kidney to the patient with the biggest expected QALY gain from transplant

Table 2. Characteristics of the recipient cohort (n=5500) used in the simulation model

	n (%)
Age (years)	
18-29	369 (6.7%)
30-39	708 (12.9%)
40-49	1,245 (22.6%)
50-59	1,576 (28.7%)
≥60	1,602 (29.1%)
Sex	
Female	2,320 (42.2%)
Ethnicity	
White	4,017 (73.0%)
Asian	727 (13.2%)
Black	626 (11.2%)
Other	140 (2.6%)
Blood group	
O	3,135 (57.0%)
A	1,590 (28.9%)
B	684 (12.4%)
AB	91 (1.7%)
Highly sensitised	468 (8.5%)
Primary renal diagnosis	
Diabetes	826 (15.0%)
Polycystic kidney disease	82 (1.5%)
Comorbidities	
Ischaemic heart disease	475 (8.6%)
Congestive heart failure	178 (3.2%)
Peripheral vascular disease	199 (3.6%)
Cerebrovascular disease	293 (5.3%)
Respiratory disease	447 (8.1%)
Liver disease	74 (1.4%)
Malignancy	262 (4.8%)
Mental illness	403 (7.3%)

Smoker	730 (13.3%)
Years on dialysis at time of listing	
Pre-dialysis	2,413 (43.9%)
<1 year	1,490 (27.1%)
1-3 years	879 (16.0%)
> 3 years	263 (4.8%)
Missing	455 (8.3%)

Table 3. Characteristics of the donor cohort (n=2200) used in the simulation model

	n (%)
Age (years)	
<30	394 (17.9%)
30-39	283 (12.9%)
40-49	503 (22.9%)
50-59	548 (24.9%)
≥60	472 (21.5%)
Blood group	
O	1,024 (46.5%)
A	892 (40.5%)
B	197 (9.0%)
AB	87 (4.0%)
History of hypertension	499 (22.7%)
UK kidney donor risk index	
High risk (≥1.35)	582 (26.5%)

Table 4. Summary of characteristics of patients who received a transplant under each allocation scheme

	Random	Waiting time	2006 NKAS	Longevity matching	QALY-maximisation
Mean age - years (SD)	51.4 (12.8)	52.5 (12.3)	46.6 (12.5)	46.3 (12.6)	41.8 (10.7)
Age group - years					
18-29	7%	5%	10%	10%	15%
30-39	12%	11%	19%	20%	27%
40-49	22%	21%	28%	29%	36%
50-59	28%	30%	25%	23%	18%
≥60	31%	33%	18%	18%	4%
Female	42%	43%	44%	44%	50%
Diabetes	15%	15%	14%	14%	11%

Table 5. Average undiscounted life years and QALYs per patient for each allocation scheme

	Random allocation		Waiting time		2006 NKAS		Longevity matching		QALY-maximising	
Life years	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**
Transplant recipients (by age group)										
18-29	27.2	(24.7, 29.7)	27.2	(24.0, 30.3)	32.8	(30.3, 35.3)	31.5	(29.3, 33.7)	29.2	(27.3, 31.2)
30-39	26.5	(24.6, 28.4)	25.4	(23.5, 27.3)	29.2	(27.7, 30.8)	30.1	(28.6, 31.7)	27.5	(26.2, 28.8)
40-49	23.4	(22.3, 24.6)	22.2	(21.0, 23.3)	23.4	(22.4, 24.5)	22.6	(21.6, 23.6)	23.4	(22.5, 24.4)
50-59	15.2	(14.5, 15.9)	15.0	(14.3, 15.7)	14.5	(13.8, 15.2)	14.5	(13.7, 15.2)	15.6	(14.7, 16.6)
>60	11.2	(10.7, 11.6)	11.4	(11.0, 11.9)	10.7	(10.2, 11.3)	11.0	(10.4, 11.6)	13.2	(11.5, 14.8)
Transplant recipients (all)	18.0	(17.5, 18.5)	17.1	(16.7, 17.6)	21.1	(20.5, 21.7)	21.2	(20.7, 21.8)	23.6	(23.0, 24,2)
No transplant (all)	8.9	(8.8, 9.1)	9.0	(8.9, 9.1)	9.0	(8.9, 9.1)	6.8	(6.7, 6.9)	6.5	(6.4, 6.6)
QALYs	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**
Transplant recipients (by age group)										
18-29	22.4	(20.4, 24.5)	22.4	(19.8, 24.9)	27.1	(25.0, 29.2)	26.0	(24.1, 27.8)	24.1	(22.5, 25.7)
30-39	21.4	(19.9, 22.9)	20.6	(19.1, 22.2)	23.8	(22.5, 25.1)	24.5	(23.2, 25.8)	22.4	(21.3, 23.5)
40-49	18.9	(18.0, 19.9)	17.9	(17.0, 18.8)	18.9	(18.0, 19.8)	18.3	(17.5, 19.1)	19.1	(18.3, 19.9)
50-59	12.3	(11.7, 12.9)	12.1	(11.6, 12.7)	11.7	(11.1, 12.3)	11.7	(11.1, 12.3)	12.7	(12.0, 13.5)
>60	9.0	(8.7, 9.4)	9.2	(8.8, 9.6)	8.7	(8.2, 9.1)	8.9	(8.4, 9.4)	10.7	(9.3, 12.0)
Transplant recipients (all)	14.6	(14.2, 15.0)	13.9	(13.5, 14.2)	17.1	(16.6, 17.6)	17.2	(16.8, 17.7)	19.3	(18.8, 19.8)
No transplant (all)	6.9	(6.8, 7.0)	6.9	(6.9, 7.0)	7.0	(6.9, 7.1)	5.2	(5.1, 5.3)	5.1	(5.0, 5.1)

Table ~~26~~. Cost-effectiveness results for transplant recipients, ~~patients who remained on the waiting list~~patients who did not receive a transplant and all patients combined

	Transplant recipients		~~Waiting list patients~~No transplant		All patients				
	Absolute c~~C~~osts	Absolute QALYs	Absolute c~~C~~osts	Absolute QALYs	Absolute c~~C~~osts	Absolute QALYs	Incremental costs	Incremental QALYs	ICER
Longevity matching	£632,382,864	44,704	£841,064,018	20,961	£1,473,446,881	65,665	-	-	-
QALY-maximisation	£680,552,945	48,045	£818,130,717	20,504	£1,498,683,661	68,549	£25,236,780	2884	£8,751
Random	£590,657,199	40,236	£1,088,809,775	26,328	£1,679,466,974	66,563	£180,783,313	-1986	Dominated
Waiting time	£584,489,615	39,496	£1,099,379,875	26,572	£1,683,869,490	66,068	£185,185,829	-2481	Dominated
2006 NKAS	£624,864,970	44,040	£1,097,473,021	26,529	£1,722,337,991	70,569	£223,654,330	2020	£110,741

Table 3. Summary of characteristics of patients who received a transplant under each allocation scheme

	Random	Waiting time	2006 NKAS	Longevity matching	QALY maximisation
Mean age - years (SD)	51.4	52.5	46.6	46.3	41.8
Age group - years					
18-29	7%	5%	10%	10%	15%
30-39	12%	11%	19%	20%	27%
40-49	22%	21%	28%	29%	36%
50-59	28%	30%	25%	23%	18%
≥60	31%	33%	18%	18%	4%
Female	42%	43%	44%	44%	50%
Diabetes	15%	15%	14%	14%	11%

Figure 1. Structure of the simulation model

Figure 2. Cost-effectiveness plane showing the relative positions of the 5 allocation schemes in terms of both total costs (vertical axis) and total QALYs (horizontal axis) for all patients

Figure 1.

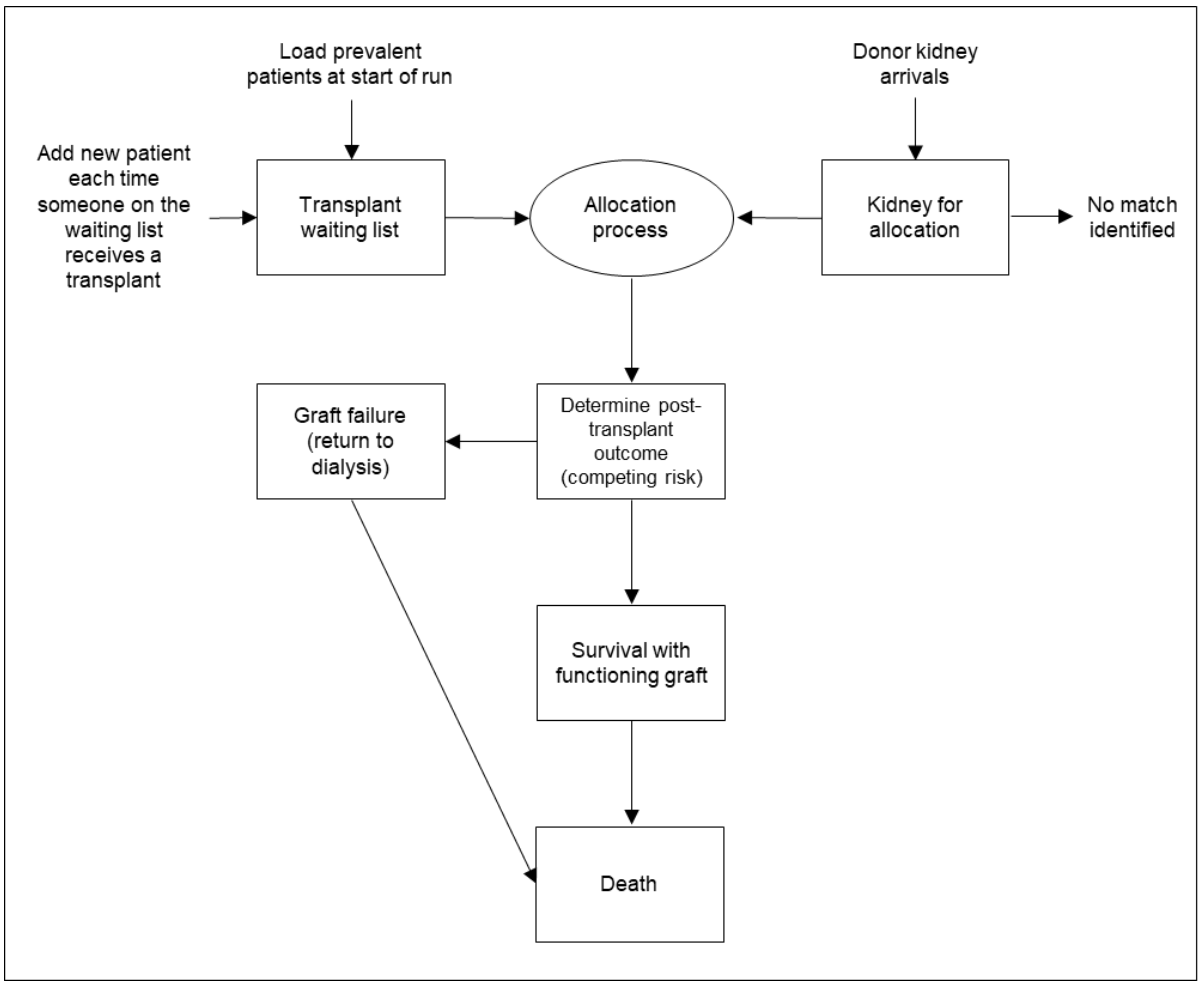
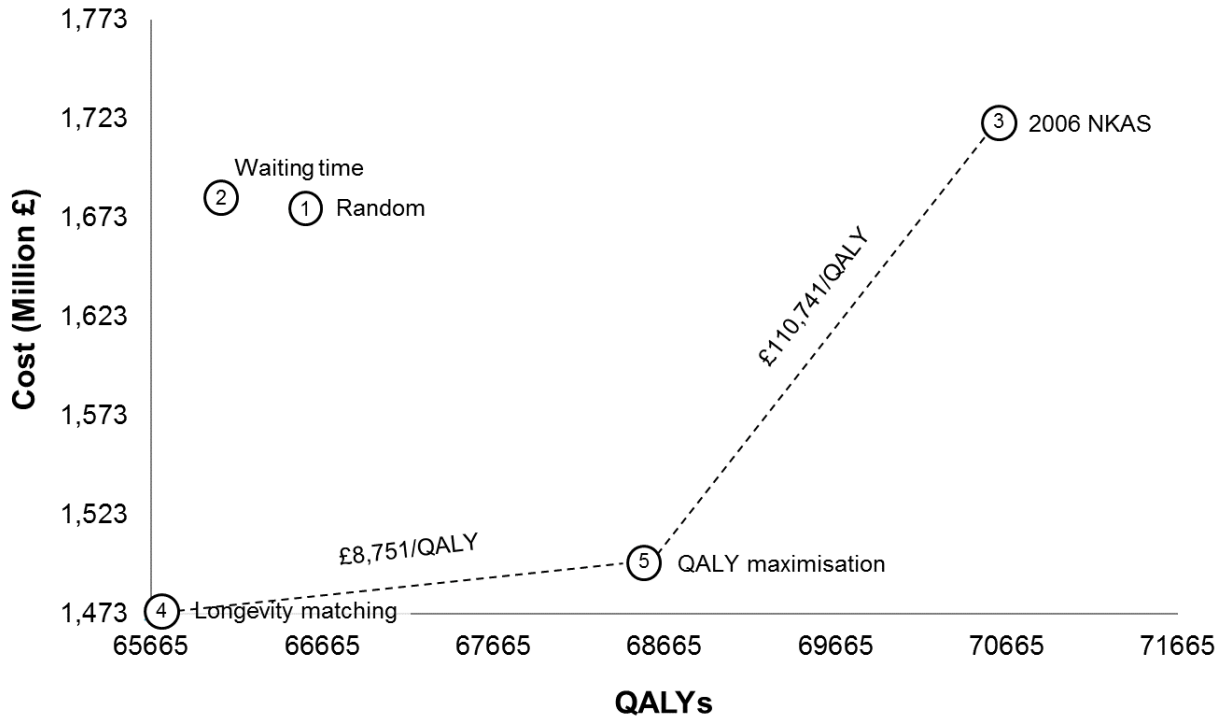

Load prevalent patients at start of run
Donor kidney arrivals
Add new patient each time someone on the waiting list receives a transplant
Transplant waiting list
Allocation process
Kidney for allocation
No match identified
Graft failure (return to dialysis)
Determine post-transplant outcome (competing risk)
Survival with functioning graft
Death

Figure 2.


1,773
1,723
1,673
1,623
1,573
1,523
1,473
Cost (Million £)
65665
66665
67665
68665
69665
70665
71665
QALYs
Waiting time
2
1
Random
3
2006 NKAS
£110,741/QALY
£8,751/QALY
5
QALY maximisation
4
Longevity matching